PERFORMANCE LIFE OF ASPHALT CONCRETE OVERLAYS GOVERNED BY FATIGUE CRACKING VARIABLES

FINAL REPORT

RP 111B

to

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Research Supervisor
Idaho Transportation Department
Boise, ID 83707

by

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ITD Grant 91-21 U of I Project 128-K439

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ABSTRACT

Selection of overlay thickness is dependent on site conditions and is used with knowledge of relative asphalt concrete toughness in order to develop a specific fatigue cracking performance life. In this study, a procedure is developed and the results are shown for a mechanistic approach to the prediction of fatigue cracking in asphalt concrete overlays.

The procedure consists of:

1. Establishment of field variables (e.g. existing pavement thickness and surface cracking condition, subgrade soil and base moduli, seasonal lengths and corresponding overlay moduli),
2. Use of a pavement layer computer program to determine strains in predetermined increments of overlay depth,
3. Establishment of overlay basic fatigue life equation based on relative asphalt concrete toughness predicted from resilient modulus and indirect tensile strength tests on laboratory specimens of overlay mixture.

4. Application of cumulative damage theory (Miner's rule) for each overlay increment with a predetermined seasonal relationship in order to "model" semi-controlled fatigue cracking progression from bottom-most overlay increment to surface of overlay,
5. Calculation of cumulative 18 kip ESAL when fatigue cracking reaches overlay surface,
6. Addition of further 18 kip ESAL to cause pavement roughness near terminal serviceability, and
7. Use of total ESAL (sum of 5. and 6.) as an estimated fatigue cracking performance life to assist in selection of overlay thickness.

Results indicate that the performance life is mainly proportional to overlay thickness and to lack of cracking and faulting of the existing (old) asphalt concrete surface. Implication is that a good correlation is needed between cracking condition of the existing asphalt concrete surface and its "slab-modulus" analog for computer program overlay strain calculation. This can be an objective of a pavement management program. The soil modulus was found to have negligible effect for the range of site variables and for the incremental overlay cracking procedure used.

The estimated fatigue cracking performance lives (total ESAL) are approximately 7 times those lives corresponding to the method of spontaneous fatigue cracking up through the overlay when the bottom-most overlay cracks. This indicates that the total ESAL predicted by the procedure in this study should not require the use of a "field factor" multiplication constant that has been conventionally used in the past.

Numerical examples are shown in the report for selecting overlay thickness to resist fatigue cracking. These examples incorporate site variables, ESAL rate from traffic analysis and design years of performance.

The study was sponsored by the Idaho Transportation Department and was performed at the University of Idaho from November 1990 to June 1991.

CONTENTS

INTRODUCTION

A goal of the Idaho Transportation Department (ITD) is to have an asphalt concrete overlay design method which incorporates both field measurements and calculations from these measurements (e.g. deflection, soil modulus) as well as a step-by-step logical procedure that includes a combination of mechanistic, laboratory and field performance correlated methods. Mechanistic procedures relate to analytical methods such as fatigue crack establishment. Field performance procedures correlate visual and physical pavement surface measurements (such as used in ITD pavement management data base) to crack propagation and roughness development.

Fatigue cracking, being a site specific problem interconnected to some mixture properties, requires a design procedure to overcome or minimize it over a predetermined period of performance. This design procedure is the selection of overlay thickness that most closely will ensure that the pavement surface will have minimum fatigue cracking over the performance period. Minimum fatigue cracking is defined in the context that fatigue cracking will not downgrade the pavement serviceability until the end of the desired performance life is reached.

Thermal cracking and reflective cracking have a different mechanical basis for their development. Thermal cracking is associated with asphalt concrete low temperature brittleness (asphalt cement cannot stress relax at cold temperatures). This type of cracking is eliminated by using asphalt cements that are ductile at cold temperatures; this can be enhanced by using certain types of additives. Reflective cracking seems to be minimized by using construction techniques such as cracking and seating of old pcc and use of stress relieving interlayers.

Other distress are rutting and raveling. Rutting is getting to be a problem that needs a solution. It occurs from a combination of high stresses, high truck volumes, and plastic flowing mixes. Mixture design is the solution. Use of large stone mixes with higher shear modulus and strength, substituted for the small stone mixes currently in use, may help to solve the problem. Raveling in the wheelpath is minimized by good mix design practice and by paving a uniform, homogeneous mixture. Low voids in compacted tensile-tough mixes can solve this problem. Surface scarification due to studded tires causes a rough rut-like wheelpath. Surface sealers or surface materials alternatives may solve this problem.

All of the above distresses are responsible for low performance life of asphalt concrete pavements. While the objective of this project is to establish a method which ITD can use to assist in the selection of overlay thickness to minimize fatigue cracking over a performance life, this does not automatically minimize effect of other distresses over a performance life. Thus, continued improvements in mixture design, quality control, materials selection and construction methods are necessary to get more life out of asphalt concrete overlays.

OBJECTIVE

The objective of this project is to develop and evaluate a mechanistic method for selection of asphalt concrete overlay thicknesses to minimize fatigue cracking over a desired performance life. Incorporated in the method are to be current and near future field measurement and laboratory test procedures most likely used by the ITD. Performance life will be based on the fatigue cracking in the asphalt concrete overlay which leads to roughness and terminal serviceability.

PLAN

The project's plan incorporates a mechanistic approach, the application of mechanical properties from laboratory tests and the correlation of existing pavement surface cracking data.

The plan is based on decrease of pavement serviceability due to fatigue cracking. It is illustrated in Figure 1. After paving an overlay, serviceability is high and there is good surface smoothness. There are no fatigue cracks in the overlay. As traffic accumulates, the overlay undergoes fatigue (repeated strain repetitions due to wheel load passes). The fatigue life of the bottom-most "layer" of the overlay is eventually reached and vertical cracks develop in the layer. Additional wheel load passes cause the cracks to propagate progressively upward through the upper portion of the overlay. When the cracks appear on the surface, the overlay is considered to have reached its fatigue life. Its corresponding time is shown as the first region in Figure 1, and can be calculated by dividing the number of wheel passes, i.e. accumulated 18 kip ESAL, by the traffic rate, e.g. ESAL/yr. Some serviceability drop is realized; roughness increase is noticed.

The cumulated ESAL, or length of time of the first region of Figure 1, is the fatigue cracking region. It is proportional to the overlay thickness, the relative toughness of the asphalt concrete mixture using specimen tests, and perhaps pavement variables (see Summary of Procedures). The prediction of ESAL (or time) for a set of known mixture and pavement site variables and for a specific overlay thickness, is the fatigue cracking part of overlay design.

Additional ESAL (or time) is necessary for the surface fatigue cracks to further propagate, fault and spall. This causes a further decrease of serviceability (increase of roughness) to a pavement condition that requires rehabilitation. This is shown as the development of roughness region in Figure 1.

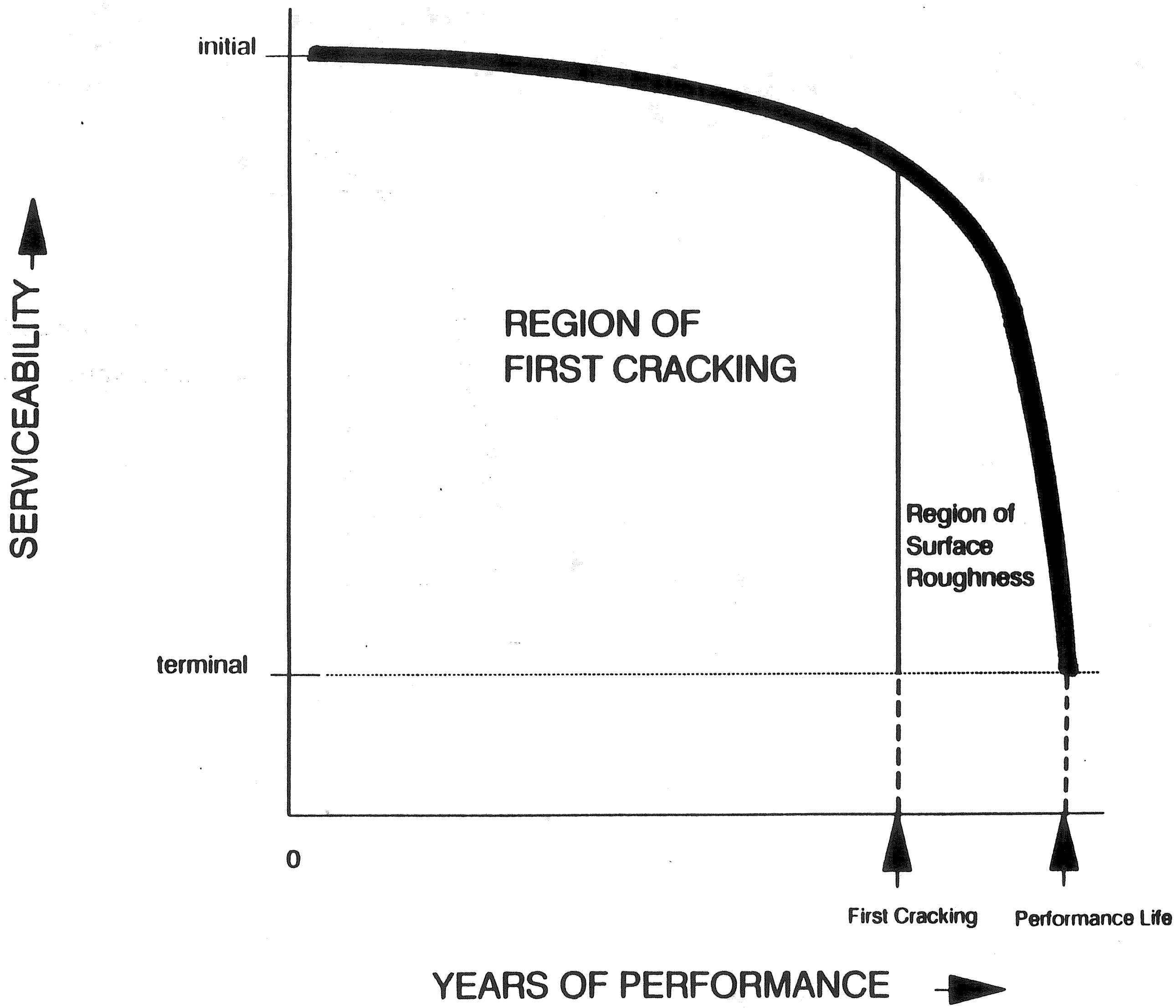

FIGURE 1. DECREASE OF OVERLAY SERVICEABILITY DUE TO FATIGUE CRACKING

The rate of decrease of serviceability (from fatigue cracking effects) in this roughness region is generally related to the same variables that are effective in the fatigue cracking region. Thus, we assume that the time of the roughness region is a specific percentage of the fatigue cracking region. The ESAL cumulated in the roughness region to terminal serviceability can be correlated through a pavement management program to determine the proportion of the roughness region.

Performance life for the overlay is considered to be the sum of ESAL (or time) of the fatigue cracking region and the roughness region. If this life is satisfactory, then the associated thickness of the overlay is considered a design thickness.

SUMMARY OF PROCEDURES

The procedures are related to the two physical sequences described in the Plan:

1. Prediction of fatigue cracking on the surface of the overlay, using a mechanistic method, and
2. Estimation of surface roughness progression to terminal serviceability.

Fatigue Cracking

Sections included here are information and the main steps for predicting cumulated ESAL to fatigue cracking of the overlay surface. These sections are: project variables, prediction of overlay strains, cumulative fatigue damage analysis and application of asphalt concrete toughness.

A. Project Variables

The following values for each variable were used in order to approximately bracket the design sequence outcome and to develop a sensitivity from a change in values.

1. Overlay thickness (ft): .1, .2, .3, .4
2. Existing pavement section thickness (ft): 1, 2 which include .3 ft and .5 ft of old asphalt concrete, respectively, on crushed stone unbound base.

   Slab-modulus of old asphalt concrete based on cracking condition (1000 psi): low cracking (low-moderate Type 1) = 70, average cracking (moderate Type 2) = 40, high cracking (map cracking, high % Type 2, 3) = 20.

   Modulus of crushed stone base (1000 psi): 16
3. Resilient modulus asphalt concrete overlay (1000 psi): 1000, 400, 125 (winter, spring-fall and summer, respectively). Seasonal lengths used: winter 3 mos., spring-fall 6 mos., summer 3 mos.

4. Modulus of subgrade soil (1000 psi): 4, 8, 16 (AASHTO type annual equivalent modulus)

B. Prediction of Overlay Strains

Strain values are required when a specific overlay thickness is combined with a specific set of values of the variables. In order to do this, the pavement was simulated in a theoretical way on computer using the Chevron 5L program. Chevron 5L is an elastic layer program in which bonding (equal strain) exists at the interface of any two layers of different materials which comprise the pavement. The loading used was the 18 kip single axle equivalent (ESAL) using dual 4500 lb. tire loads at tire pressure of 80 psi. The tire loads were considered to be 13 inches c-c.

For each set of values of the variables, radial (tensile) strains were obtained at .6 inch (theoretical) increments throughout the thickness of the overlay. Since the fatigue damage analysis method used requires assignment of lower modulus to the .6 inch incremental layers as they crack, then several computer runs are needed to find the different strains that result. For a given set of values of the variables, several groups of radial strains were used in the analysis to follow the upward crack progression.

Further explanation of the prediction of strains is given in Appendix A.

Note: Other quality strain prediction computer programs can be used. The program, however, must have the capability like Chevron 5L to calculate strains at any operator-selected depth in the overlay and pavement. This is necessary because the controlled crack propagation analysis requires strains at pre-selected .6 inch increments of depth in the overlay.

C. Cumulative Fatigue Damage Analysis

This analysis method incorporates the following two independent relationships:

1. Fatigue equation for asphalt concrete overlay, and
2. Cumulative damage equation (Miner's rule).

1. **Fatigue equation.** The fatigue equation for asphalt concrete represents its fatigue line, which is considered to be a mechanical property of the compacted asphalt concrete mixture acting as the overlay. It correlates the repeated radial tensile strains (predicted by the computer program) to the basic fatigue life (repetitions) of the asphalt concrete to sufficient onset of cracking. The following equation is intended to represent average dense-graded asphalt concrete:

$$N_f = C\ \varepsilon^{-5.16} \qquad \text{where}$$

N_f = basic fatigue life, C = constant related to position of fatigue line and ε = radial tensile strain.

Low modulus of uncracked asphalt concrete increases the value of C in the equation and increases the value of N_f. Therefore, the equation changes with the seasons. For example, summer results in the highest value of C (and N_f). The selection of C for seasonal change is described in Appendix A.

Higher than average toughness of the asphalt concrete also results in increases of the value of C in the equation; lower than average toughness decreases the value of C. The explanation of the calculation of C from relative toughness is in Appendix D. Background information on relative asphalt concrete toughness is included in the next section, D, and in Appendix C.

2. <u>Cumulative Damage Equation</u>. This is an equation that represents the sum of fractional fatigue damage in a .6 inch increment of overlay during the sequence of upward crack propagation to the surface. The damage equation has alternate forms and its use is explained in Appendix A.

Starting with the bottom-most .6 inch increment of the overlay, the repetitions to fatigue cracking is equal to the basic fatigue life of the asphalt concrete. The damage in the immediate upper .6 inch increment of the overlay is calculated and the cumulative damage equation is used along with a new basic life to obtain the repetitions to fatigue cracking for this increment. The process is repeated until all repetitions in each increment are calculated by use of the damage equation.

Seasonal effect, reflected as basic life change, is represented by the three seasonal terms in the cumulative damage equation. This effect has a marked change on the rate of damage, the highest being in the winter season (unfrozen base and soil is assumed).

The incremental use of the cumulative damage equation, including seasonal effect, is described in Appendix A.

Cumulative repetitions for the upward fatigue crack propagation in the overlay are listed in the Tables B of Appendix B for each set of values of the variables.

Expectation is that cumulative repetitions, calculated by the incremental method described, will result in a several fold increase of predicted "first crack" fatigue life of the overlay when compared to the "first crack" fatigue life of the bottom-most increment "first crack" fatigue life of the bottom-most increment only. If the overlay life is equal to the repetitions of the bottom-most increment only, the physical mechanism to be assumed is spontaneous crack propagation to the surface. In reality, the upward crack propagation is probably more controlled than this. Therefore, the incremental method used here with seasonal variation should give more realistic predictions of fatigue life for overlays.

D. Application of Asphalt Concrete Toughness

Asphalt concrete toughness is variable because the mixture of aggregates, asphalt and additives differ for each job. Thus, each mixture is expected to have different mechanical properties, e.g. resilient modulus and indirect tensile strength. These properties can be obtained as design properties when laboratory tests are performed on specimens to represent the overlay in service. The physical property, called toughness can be estimated from these properties, but the more accurate way at present is to use relative toughness. Here, a state average for values of modulus and indirect tensile strength is specified. Values obtained for a planned overlay mixture are related to the average values. The relative toughness of the planned overlay mixture (on a strain basis) is equal to:

$$\frac{(TSR)^2}{(MrR)^2} \quad \text{where} \qquad (1)$$

WHAT IS RELATIVE
& physical test
PROPS = tough

TSR = indirect tensile strength ratio and MrR = resilient modulus ratio, where ratio is designated as planned overlay value/the state average value.

The value of the C constant in the fatigue equation is adjusted upward for better-than-average toughness and downward for lower-than-average toughness. If a relative toughness is equal to 1.0, then this mixture is at state average there is no toughness adjustment of C. Average C constants are shown in Figure A-1 of Appendix A as a function of seasonal resilient modulus of the asphalt concrete, and are considered state average for the purposes of this study.

The previous relationship for relative toughness was tested for practical implications using the resilient modulus and indirect tensile strength values representing several sets of road cores. The cores were drilled by ITD from overlays of known fatigue cracking performance and sent to the U of Idaho for testing. Relative toughness was calculated for each overlay. The procedures and data are shown in Appendix C. Results are shown in Figure 2. The relative toughness generally corresponds to the overlay performance.

This indicates that the adjustment of C in the fatigue equation due to relative toughness of the overlay mixture may be practical. Adjustment of C constant is explained in Appendix D.

The laboratory, having the capability to perform the resilient modulus and indirect tension tests, can obtain relative toughness for any mixture prior to paving. The prediction of how well fatigue resistant additives perform to the cost/benefit of added life for specific overlay thicknesses is a useful example of obtaining performance information to supplement data that may or may not be obtained later from the use of field test pavements. Another useful example is the application(s) of knowing the statewide variation of mixture toughness and its effect from changes of materials.

RANKING	RELATIVE TOUGHNESS
Above Average	
I-90 (MP31)	1.37
Chinden Blvd. (44th-Coffey) Boise	1.34
SH-53 (MP53)	0.72 ?
Average	
I-15 (MP44)	1.00
Below Average	
I-84 (MP145)	0.54
I-84 (MP175)	0.26

FIGURE 2. RANKING OF ASPHALT CONCRETE OVERLAYS FOR FATIGUE CRACKING RESISTANCE BY ITD VS. RELATIVE STRAIN TOUGHNESS OF OVERLAY CORES BY LABORATORY TEST

Surface Roughness Increase

Increase of surface roughness due to fatigue cracking is related to the same variables that affect the onset of fatigue cracking, probably at the same level of influence. This assumption is used here because there are no well established mechanistic applications for prediction of ESAL to terminal roughness. Instead, the ESAL (or time) in this region of pavement performance might very well be a percent of the ESAL (or time) of the fatigue cracking region. For the purposes of this report, we recommend the following percentages based on the traffic classification characteristic:

20% for light truck traffic
15% for medium truck traffic
10% for heavy truck traffic

As an example of using the previous percentages, suppose the cumulated ESAL to observance of cracking is predicted to be 2.3×10^6 for a specified overlay. The traffic classification is medium. Therefore, the surface roughness ESAL is $.15(2.3X10^6) = 0.3x10^6$. The fatigue performance life for the overlay is $2.3x10^6 + 0.3x10^6 = 2.6x10^6$ ESAL. If the traffic rate is $0.2x10^6$ ESAL/year, then the predicted performance life for the overlay is $2.6x10^6/0.2x10^6 = 13$ years.

RESULTS AND IMPLICATIONS

The results of applying the procedures for fatigue cracking are listed as Tables B in Appendix B. (Explanation of the results in Tables B are given on the page preceding the tables). In Tables B are listed the effective repetitions for each overlay thickness and for each set of values of the variables. The effective repetitions are cumulative; the repetitions representing the uppermost .6 inch increment analyzed is the predicted fatigue cracking life ("first cracking" appearance on overlay surface).

Evaluation of Tables B indicates that the following two variables are most effective for changing fatigue cracking life: overlay thickness and cracking condition (analogged using Mr of old or existing asphalt concrete surfacing). Thickness of existing pavement section has some effect. Subgrade soil modulus (in the range of values used) has little or no effect. The soil modulus has some effect on the life of the bottom-most increment in the overlay, especially for thicker overlays; its effect seems negligible for the cumulated fatigue life of the .6 inch increments in the overlay and for the thinner overlays.

Since the assumption that surface roughness life (discussed in the previous main section) is proportional to first cracking fatigue life on overlay surface then the results in Tables B can be considered proportional to the (total) fatigue performance life of the overlay.

The results of Tables B are displayed on Figure 3. Here, the first cracking fatigue life in ESAL corresponding to the four overlay thicknesses is shown with three categorized values of surface cracking of the old asphalt concrete pavement. ESAL for overlays on a 1 ft. (12 in.) thick existing (old) pavement section are shown as the predominant bar graphs. However, for the average old asphalt concrete cracking condition, ESAL is also shown for overlays on a 2 ft. (24 in.) thick existing pavement

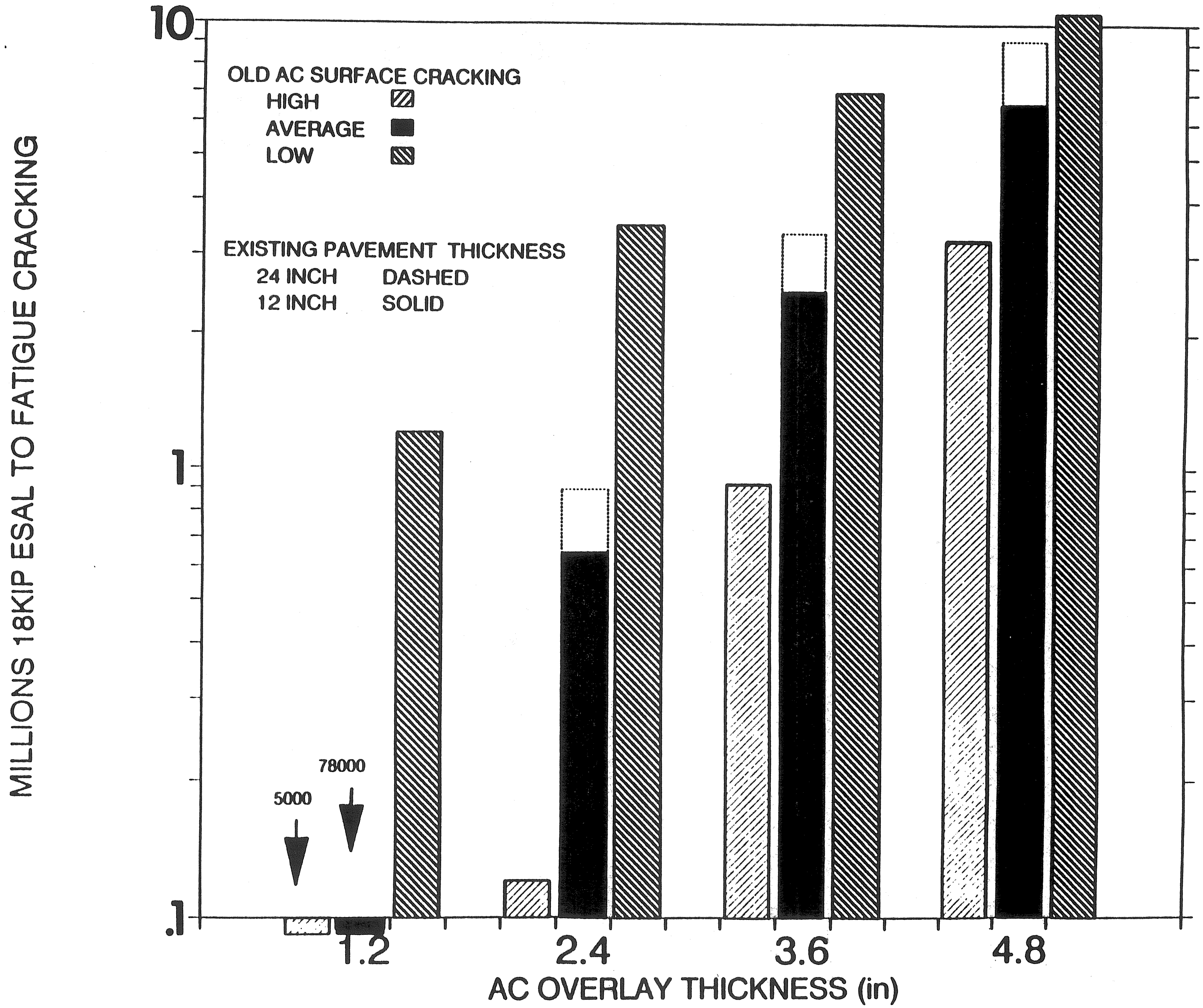

FIGURE 3. PREDICTED FATIGUE CRACKING EQUIVALENTS FOR DIFFERENT OVERLAY THICKNESSES

section. For the range of values 4000 to 16000 psi used in the mechanistic method, the effect of the subgrade soil resilient modulus on overlay life was determined not to be a factor in the Figure 3 development.

Results and implications from Tables B and Figure 3 indicate the following:

1. The cumulative (effective) ESAL repetitions for upward fatigue crack propagation to the uppermost .6 in. incremental of overlay evaluated is seven (7) times the ESAL repetitions of the bottom-most .6 in. increment.

   The implication is that if overlay ESAL repetitions are predicted by mechanistic methods using the bottom-most increment of the overlay then a "field factor" (ESAL multiplier) of 7 is required to achieve the same prediction from the upward progression of cracking method used in this project. Thus, the controlled upward fatigue cracking progression in the overlay appears to be a more realistic assumption than upward, uncontrolled, spontaneous crack propagation to the overlay surface for asphalt concrete. No "field factors" are required with the application of this controlled cracking assumption.

2. Fatigue cracking ESAL repetitions for overlays on 2 ft. (24 in.) thick existing pavements are 1.3 times greater than the repetitions on 1 ft (12 in.) pavements.

3. Fatigue cracking ESAL repetitions for overlays on low-cracked old asphalt concrete pavements are at least twice those on old asphalt concrete that are average cracked, and at least four times those on highly cracked old asphalt concrete.

   Implication of 2 and 3 is that the cracking condition of the old asphalt concrete surfacing affects the overlay fatigue life much more than the thickness of the existing pavement section. These thicknesses of pavement sections (1 ft. or more) are found on primary and interstate pavements. Thus, careful analysis of the cracking condition of the old asphalt concrete surfacing is necessary to achieve accurate predictions of overlay fatigue life.

A method for this cracking analysis needs to be developed, with a visual technique predominant, since determination of old asphalt concrete "slab modulus" is required. Deflection devices which produce large surface area loaded basins may also be applicable. A well-developed method will enable:

<u>a.</u> establishing a reliable analog for slab modulus of old asphalt concrete to be used in Chevron 5L or equivalent programs, and

<u>b.</u> establishing a "support modulus" for the old asphalt concrete to use with deflection measurements when other methods to predict overlay thickness are used.

4. The first cracking ESAL repetitions for overlays are not affected by the subgrade soil resilient modulus in the range of values used. This indicates that a resilient modulus value of 8000 psi (mid-range of values used) would be reasonable for use in running the Chevron 5L program with the mechanistic method.

5. Figure 3 can be used as an aid to select overlay thickness. The figure is set up so that interpolation can be used. Additional ESAL repetition are added (by percent) to account for surface roughness increase to terminal serviceability.

Examples of overlay thickness selection are illustrated in the next main section.

6. Figure 3 shows results for state average toughness of asphalt concrete. Overlays that will have more or less toughness will have more or less fatigue cracking ESAL repetitions than shown in Figure 3. A future benefit will be to construct a "sensititiy to toughness" addition to Figure 3 using the mechanistic method with different C constraints in the fatigue equation adjusted for toughness (see adjustment of C in Appendix D). This will enable the quick selection of overlay thickness using relative toughness calculated from laboratory tests on the asphalt concrete.

SELECTION OF OVERLAY THICKNESS

Four numerical examples for obtaining overlay thickness are shown in this section. They illustrate the application of fatigue cracking life, using Figure 3, and roughness increase to terminal serviceability, using percentages. Thus, the examples follow the idea of the two regions of the serviceability curve in Figure 1.

In these examples, the pavement conditions and variables are within the range of values used in this study for the development of Figure 3, and coincide with the recommended percent increase of ESAL in the roughness region of the serviceability curve. In addition, the state average asphalt concrete toughness is assumed for the overlays.

OVERLAY FOR PAVEMENT A

A. Conditions old asphalt concrete has average cracking
traffic class is medium
exist. pavement thickness = 1 ft
future ESAL rate = 80,000 per yr
Performance period (initial to terminal serviceability) = 10 yr

B. Thickness Selection

Total ESAL = 10 yr x 800,000 ESAL/yr = 800,000

Roughness ESAL increase percentage = 15% for medium traffic (after ESAL fatigue cracking)

(ESAL fatigue cracking)(1.15) = 800,000

ESAL fatigue cracking = 700,000

Refer to Figure 3 w/700,000 ESAL requirement on average cracked old asphalt concrete, pavement 1 ft

Ans: 2.4 in (.2 ft) overlay thickness required

OVERLAY FOR PAVEMENT B

A. **Conditions** old asphalt concrete has average cracking
traffic class is heavy
exist. pavement thickness = 2 ft
future ESAL rate = 290,000 per yr
Performance period (initial to terminal serviceability = 12 yr

B. **Thickness Selection**

Total ESAL = 12 yr x 290,000 ESAL/yr = 3,480,000

Roughness ESAL increase percentage = 10% for heavy traffic (after ESAL fatigue cracking)

(ESAL fatigue cracking)(1.10) = 3,480,00

ESAL fatigue cracking = 3,200,000

Refer to Figure 3 w/3,200,000 ESAL requirement on average cracked old asphalt concrete, pavement 2 ft

Ans: 3.6 in (.3 ft) overlay thickness required

OVERLAY FOR PAVEMENT C

A. Conditions

old asphalt concrete has high cracking
traffic class is medium
exist. pavement thickness = 1 ft
future ESAL rate = 134,000 per yr

Performance period (initial to terminal serviceability) = 12 yr

B. Thickness Selection

Total ESAL = 12 yr x 134,000 ESAL/yr = 1,600,000

Roughness ESAL increase percentage = 15% for medium traffic (after ESAL fatigue cracking)

(ESAL fatigue cracking)(1.15) = 1,600,000

ESAL fatigue cracking = 1,400,000

Refer to Figure 3 w/ESAL requirement on high-cracked old asphalt concrete, pavement 1 ft

Interpolation in Figure 3 is required between 2.4 in. and 3.6 in.

Ans. 3.0 in (.25 ft) overlay thickness required

OVERLAY FOR PAVEMENT D

A. Conditions old asphalt concrete has low cracking

Need to find planed (scarified) depth into old asphalt concrete. This will be thickness of overlay to resist fatigue. Overlay mix to be rut resistant.

traffic class is medium

existing pavement thickness = 1 ft

Future ESAL rate = 190,000 per yr

Performance period (initial to terminal serviceability) = 14 yr

B. Thickness Selection

Total ESAL = 14 yr x 190,000 ESAL/yr = 2,660,000

Roughness ESAL increase percentage = 15% for medium traffic (after ESAL fatigue cracking)

(ESAL fatigue cracking)(1.15) = 2,660,000

ESAL fatigue cracking = 2,300,000

Refer to Figure 3 w/2,300,000 ESAL requirement on low-cracked old asphalt concrete, pavement 1 ft

Interpolation in Figure 3 is required between 1.2 in. and 2.4 in.

Ans. 2.0 in (.17 ft) overlay thickness required

APPENDICES

APPENDIX A

PROCEDURE FOR MECHANISTIC CALCULATION OF FIRST CRACK EFFECTIVE FATIGUE LIFE OF ASPHALT CONCRETE OVERLAY

This appendix is divided into four sections:

1. Mechanical properties and pavement thicknesses
2. Computer model used for tensile strain determination
3. Calculation procedure for first crack effective life repetitions
4. Numerical example of calculation procedure

1. Mechanical Properties and Pavement Thicknesses

The following are the variables incorporated into the first crack life procedure from which results are shown up front in the report:

Overlay thicknesses (in.) = 1.2, 2.4, 3.6 and 4.8

Existing pavement thicknesses (in.) = 12 and 24

includes: old asphalt concrete thickness (in.) = 4 and 6

crushed stone (untreated) base thicknesses (in.) = 8 and 18

soil subgrade thickness = infinity

Modulus of asphalt concrete overlay (1000 psi) = 1000, 400 and 125 for uncracked condition winter, spring-fall, summer, respectively, and = 70 for cracked condition all seasons. These seasonal moduli are effective slab moduli, i.e. moduli of cores or aged specimens of the overlay mix, which, after first crack, are decreased to 70 (1000 psi) due to initiation of insitu slab cracking at the surface.

Modulus of old (existing) asphalt concrete (1000 psi) = 70, 40, 20 representing low, moderate and severe surface cracking, respectively (effective slab moduli)

Resilient modulus of subgrade soil (1000 psi) = 16, 8, 4 representing annual effective modulus for high, moderate and low stiffness, respectively

Resilient modulus of crushed stone base (1000 psi) = 16

Poisson's ratio = .35, .40, .35, .40 for asphalt concrete overlay, old asphalt concrete, crushed stone, base and subgrade soil, respectively.

2. Computer Model for Calculation of Overlay Tensile Strain

The Chevron 5L computer program was used to determine the tensile radial bending strain in asphalt concrete overlay layers due to the effect of an 18-kip single axle load (ESAL) applied on the surface of the overlay. The load is considered to be the effect of one set of dual wheels, 4500 lb. each at 80 psi tire pressure, placed 13 in. c-c.

The resulting tensile strain in the asphalt concrete overlay is the algebraic summation of the strain under one wheel (R=0) and of the strain under the other wheel placed 13 in. away from the first one (R=13). Thus, the strain due to the wheel 13 in. away is superimposed on the strain directly underneath the other wheel. If the summation is negative (the radial strain is compression) then the asphalt concrete is not considered to be weakened by fatigue that forms cracks. Fatigue is only calculated when the summation is positive (the radial strain is tension).

A set of strains is calculated for a given set of input variables (moduli, Poisson's ratios and thicknesses). The set of strains corresponds to the strain in each of the bottom of theoretical, incremental overlay "layers" .6 in. thick. For example: an asphalt concrete overlay of 3.6 in. (.3 ft) thick would be theoretically divided into .6 in. thick incremental layers. This is to account for incremental contributions of remaining cracking life in the overlay as the crack propagates upward to the surface. The crack initiates first in the bottom incremental layer (radial tensile strains highest). When this incremental layer cracks its effective slab modulus is assigned to be 70,000 psi for obtaining the succeeding set of strains for the above layers of the overlay, and the process is repeated until the effective cracking life (sum of incremental contributions of fatigue repetitions life) is determined for the overlay. The contribution of the topmost incremental .6 in. layer is not used because of possible inaccuracy with calculations due to the slow convergence in the computer model (the topmost layer is at the boundary condition, which is the pavement surface).

3. Calculation Procedure for First Crack Effective Life Repetitions

The following is the procedure used to calculate the first crack effective life repetitions, that is, the number of accumulated ESAL repetitions (reps) for the .6 in. incremental layers comprising a total overlay thickness. These repetitions are considered to be a prediction of when fatigue cracks due to wheel load will start to appear on the overlay surface. (The additional ESAL repetitions to terminal serviceability, i.e. due to roughness from fatigue cracking is not included here. This added overlay performance life increment is discussed up-front in the report.)

First, the basic repetitive ESALs are calculated for each .6 inch increment of the overlay layer. The basic reps is the number of repetitions per season to first crack initiation for each .6 inch increment. The basic reps equation is

$$N_f = C\epsilon^{-5.16} \qquad \text{(Eq. 1)}$$

N_f = basic reps (number of ESAL)

C = constant that is inversely proportional to the slab modulus(M_r) of the uncracked portion of overlay. See Figure A-1 for finding C for average asphalt concrete mix. The following C constants from Fig. A-1 were used to obtain the overlay first crack life data in this report:

4.7×10^{-15} for Mr = 1,000,000 psi,

1.7×10^{-14} for Mr = 400,000 psi, and

infinity for Mr = 125,000 psi.

ϵ = tensile bending strain in the bottom of the .6 inch incremental layer being analyzed

The effective reps is then calculated for each .6 inch incremental layer using the following equation

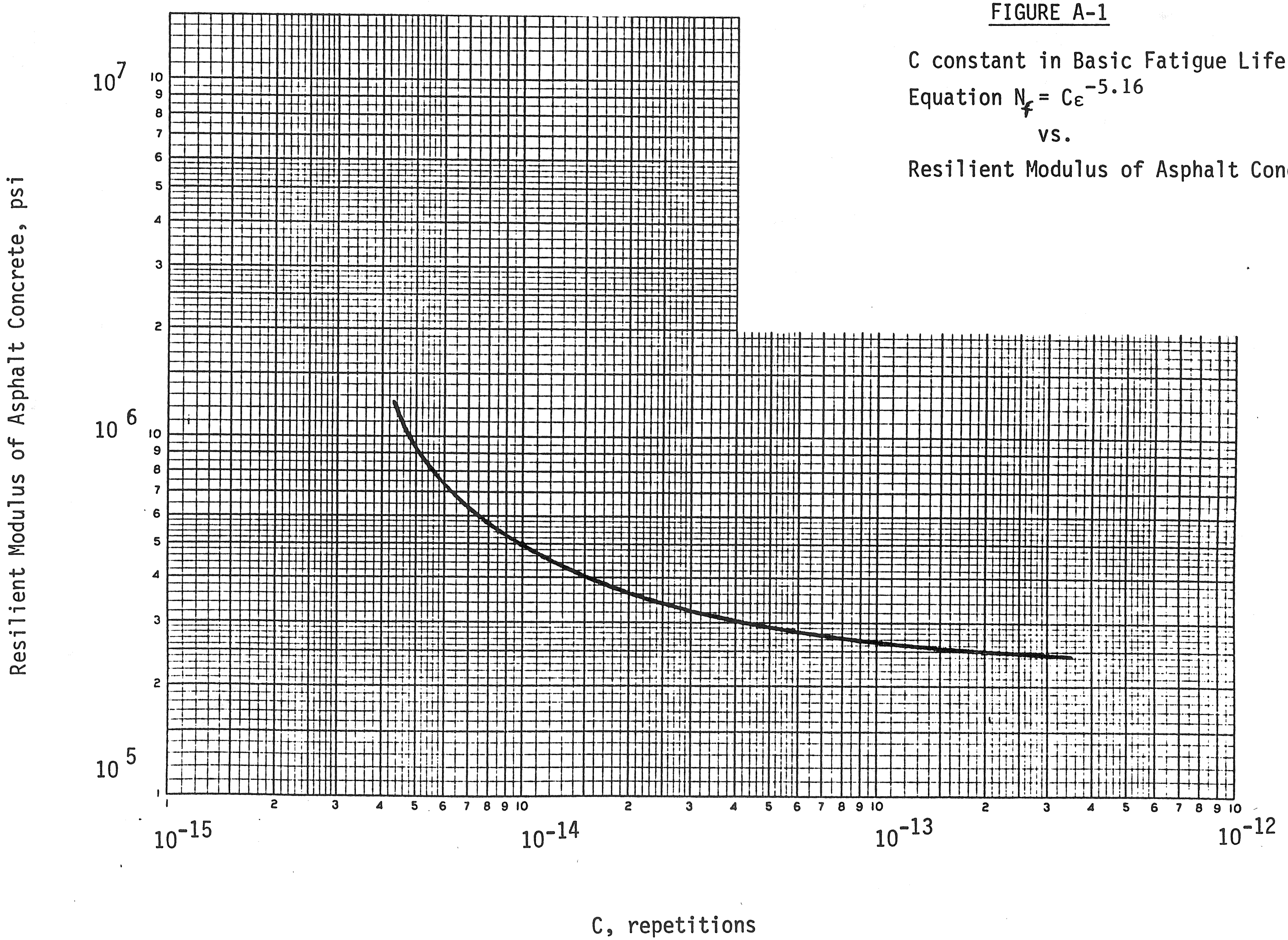

FIGURE A-1

C constant in Basic Fatigue Life
Equation $N_f = C\varepsilon^{-5.16}$
vs.
Resilient Modulus of Asphalt Concrete

$$N\sum \frac{f_i}{N_{f_i}} = 1 \qquad \text{(Eq. 2)}$$

where

N = effective reps

f_i = fraction of time (part of a year) that the overlay (any of its incremental layers) is subjected to a specific seasonal effect for which the slab modulus of the asphalt concrete is constant due to similar seasonal temperature. The following f_i are used in this report:

= .5 years for Mr = 400,000 psi, corresponding to spring-fall

= .25 years for Mr = 1,000,000 psi, corresponding to winter

= .25 years for Mr = 125,000 psi, corresponding to summer

N_{fi} = basic reps corresponding to the seasonal Mr = 400,000, 1,000,000 and 125,000 psi, calculated from Eq. 1

<u>Note</u>: The seasonal f_i may vary depending on location. The above f_i used here are assumed to be an average condition.

The effective reps calculated using Eq. 2 represent the number of ESAL repetitions to initiate a first crack only in the incremental layer being analyzed. The effective reps shown in Tables B (Appendix B) are the cumulative effective reps, which is the sum of the effective reps for the incremental layer being analyzed plus the effective reps representing the number of repetitions for a crack to initiate in the bottom incremental layer and propagate upwards through the incremental layer being analyzed. The cumulative effective reps representing the uppermost incremental layer to be analyzed (.6 in. incremental layer immediately below the topmost .6 in. incremental layer of the overlay) is considered to be the first crack life of the overlay.

Since each incremental layer is under the cracking fatigue process, the incremental layers above it, which are also not yet cracked, may also undergo some fatigue damage, resulting in a loss of a portion of their first crack life. The equation that is used to calculate the fraction of first crack life used up in an incremental layer before it cracks is

$$N_c \sum \frac{f_i}{N_{fi}} = F \qquad \text{(Eq. 3)}$$

N_c = cumulative number of effective reps to first crack initiation for all the incremental layers below this layer

N_{fi} = basic reps for the uncracked incremental layer located immediately above the cracked lower layers due to the tensile bending strain at the bottom of this incremental layer

f_i = (see f_i definition for Eq. 2)

F = fraction of life used up in this uncracked incremental layer

Then,

$F_i = 1 - F$ = fraction of life remaining in the uncracked incremental layer. (When F_i is greater than .95, we assume for practical purposes that there is no life used up in this layer due to repetitions arising from the lower incremental layer fatigue process; thus in this case, F_i is assumed to be 1)

Finally, to calculate the effective reps, N, for this incremental layer the following equation is used:

$$N\sum\frac{f_i}{N_{fi}} = F_i \qquad \text{(Eq. 4)}$$

A numerical example follows.

4. Numerical Example of Calculation Procedure

This is a numerical example for calculating the first crack life in (cumulative effective reps) of an overlay. Assume a pavement section with the following variables:

Pavement section thickness = 12 in. (asphalt concrete = 4 in

Overlay thickness = 2.4 in.

Overlay Mr* (1000 psi) = 1000, 400, 125 uncracked (= 70 when cracked)

Old (existing) asphalt concrete Mr* (1000 psi) = 40

Crushed stone base Mr (1000 psi) = 16

Soil subgrade Mr** (1000 psi) = 4

*<u>Note</u>: *Mr is effective slab modulus of asphalt concrete

**Mr is annual effective, resilient (total) modulus of subgrade soil under pavement

Data from the Chevron 5L computer program are shown in Table A-1. The dashes in the strain column indicate that the incremental layer of overlay is in compression and is assumed not to be experiencing any tensile-cracking fatigue damage. Superposition of strains is done by obtaining strains at R=0 and R=13, and then adding them algebraically to determine the total strain for the incremental layer. To calculate basic reps for incremental layer 1 (the bottom most increment layer), Eq. 1 is applied as follows

For spring-fall, Mr = 400,000 psi
$N_f = (1.7\text{x}10^{-14})(258\text{x}10^{-6})^{-5.16}$
$N_f = 5.58\text{x}10^{4}$ Reps

For winter, Mr = 1,000,000 psi
$N_f = (4.7\text{x}10^{-15})(187\text{x}10^{-6})^{-5.16}$
$N_f = 8.12\text{x}10^{4}$ Reps

For summer, Mr = 125,000 psi
$N_f = \infty$ Reps

The other values for basic reps of the asphalt concrete overlay (located in Table A-1) are found in the same way. Here, the seasonal Mr's remain the same, but the strains for the incremental layers are different, giving different basic reps.

The effective reps are calculated from the equations which use the basic reps.

TABLE A-1 DATA FOR EXAMPLE

CONDITION	Z* (IN.)	STRAIN (10E-6) R=0	STRAIN (10E-6) R=13	TOTAL STRAIN	BASIC REPS
2.4"	0.6	-	-		
Mr=400,000	1.2	-	-		
	1.8	137	-31	106	5,490,000
	2.4	313	-55	258	55,800
1.8"	0.6	-	-		
Mr=400,000	1.2	46	-19	27	6.38E+09
.6"	1.8	268	-45	223	118,000
Mr=70,000					
1.2"	0.6	-	-		
Mr=400,000	1.2	152	-28	124	2,450,000
1.2"					
Mr=70,000					
.6"	0.6	-	-		
Mr=400,000					
1.8"					
Mr = 70,000					
2.4"	0.6	-	-		
Mr=1,000E3	1.2	-	-		
	1.8	104	-21	83	5,370,000
	2.4	225	-38	187	81,200
1.8"	0.6	-	-		
Mr=1,000E3	1.2	60	-16	44	142,000,000
.6"	1.8	234	-40	194	67,100
Mr=70,000					
1.2"	0.6	-	-		
Mr=1,000E3	1.2	198	-30	168	141,000
1.2"					
Mr=70,000					
.6"	0.6	-	-		
Mr=1,000E3					
1.8"					
Mr=70,000					

Note: Z is vertical distance downwards from new pavement surface (top of overlay) to bottom of specified overlay incremental layer.

Effective reps of incremental layer 1 is found by using Eq.2

$$N_1\left[\frac{.5}{5.58x10^4} + \frac{.25}{8.12x10^4} + \frac{.25}{\infty}\right] = 1$$

Solving for N_1

N_1 = $8.31x10^4$ Reps (subscript 1 denotes first or bottom most incremental layer)

$N_1 = N_c$ in this case for layer 1 because there is no incremental layer below it

Before the effective reps for incremental layer 2 (located above incremental layer 1) can be determined, the fraction of life, F, used up in incremental layer 2 by N_1 reps resulting from the incremental layer 1 directly beneath it, is calculated using Eq. 3.

$$8.31x10^4\left[\frac{.5}{5.49x10^6} + \frac{.25}{5.37x10^6} + \frac{.25}{\infty}\right] = F$$

$$F = 1.14x10^{-2}$$

The fraction of life remaining in incremental layer 2 is at the time that layer 1 cracks is

$$1 - 1.14x10^{-2} = .989$$

Since .989 is greater than .95, then 1-F for practical purposes is considered to be 1. Therefore, no life has been used up in incremental layer 2 by N_1 reps. Eq. 4 is then used to calculate the effective reps, N_2, for incremental layer 2 with $F_i = 1$

$$N_2\left[\frac{.5}{1.18x10^5} + \frac{.25}{6.71x10^4}\right] = 1$$

$$N_2 = 1.26x10^5 \text{ Reps}$$

The cumulative effective reps for incremental layer 2 includes both N_1 reps and N_2 reps. Thus, the effective reps for incremental layer 2 is

$$8.31x10^4 + 1.26x10^5 = 2.09x10^5 \text{ reps}$$

Eq. 3 is used to calculate the life used up in incremental layer 3, the next uppermost incremental layer of the 2.4 in. overlay

$$1.26x10^5\left[\frac{.5}{6.38x10^9} + \frac{.25}{1.42x10^8} + \frac{.25}{\infty}\right] = F$$

$$F = 2.32x10^{-4}$$

<u>Note</u>: Tensile strain fatigue repetitions only occurred in this incremental layer <u>after</u> increment layer 1 cracked. Thus, $1.26x10^5$ reps is used as N_c. Therefore, the life used up in incremental layer 3 by N_2 reps is $2.32x10^{-4}$. The fraction of life remaining in incremental layer 3 is

$$1 - 2.32x10^{-4} = .999$$

Since .999 is greater than .95, then no life has been used up in incremental layer 3. Eq. 4 is used to calculate the effective reps for incremental layer 3 with $F_i = 1$

$$N_3\left[\frac{.5}{2.45x10^3} + \frac{.25}{1.41x10^{-5}} + \frac{.25}{\infty}\right] = 1$$

$$N_3 = 4.86x10^3 \text{ reps}$$

The cumulative effective reps for incremental layer 3 is assumed to be that also for the overlay since the incremental layer above it is the uppermost .6 in. incremental layer of the overlay. Thus, this is the number of reps required to initiate a first crack in the bottom layer and propagate it to the pavement surface, i.e. through incremental layers of the overlay. In this example, the cumulative effective reps (First Crack Life) is 2.14×10^5 reps, as calculated below

$$N_1 + N_2 + N_3 = \text{sum of effective reps for each layer}$$

$$8.31 \times 10^4 + 1.26 \times 10^5 + 4.86 \times 10^3$$

$$= 2.14 \times 10^5 \text{ reps}$$

The cumulative effective reps (First Crack Life) of the overlays are reported in Tables B (Appendix B). They are calculated in the same way as shown in this example.

APPENDIX B

EFFECTIVE ESAL REPETITIONS TO FIRST CRACKING AT OVERLAY SURFACE

Tables B-1 through B-8 represent the results of using cumulative damage relationship with Chevron 5L computer program data. Effective repetitions is defined as the predicted number of ESAL required to establish visible first cracking on the overlay surface due to wheel load fatigue.

The tables are organized as follows

Table Number	Thickness of Overlay, in.
B-1, B-2	1.2
B-3, B-4	2.4
B-5, B-6	3.6
B-7, B-8	4.8

The first table in each overlay thickness grouping (odd number) are the results on an existing 12 in. pavement section. The second table (even number) are the comparison of results on an existing 12 in. pavement section to the results on an existing 24 in. pavement section.

The variables and overlay incremental layer numbers are shown on the top of each table. For a specific set of variables, the basic repetitions are shown (overlay fatigue property "Nf", see Appendix A). To the right are the calculated cumulative effective ESAL repetitions to first crack in the particular incremental overlay layer shown. The last entry of effective repetitions, corresponding to the highest overlay incremental layer evaluated, is considered to be the overall cumulative effective repetitions for the overlay. This is the predicted ESAL for first crack appearance on the overlay surface due to wheel load fatigue.

The uppermost incremental overlay layer (top .6 in. layer) is not evaluated due to apparent limitations to accurately determine a realistic level of strain at this boundary condition, i.e. surface of overlay. Thus, we assumed the cumulative effective repetitions calculated from the Chevron 5L program for the .6 in. layer immediately below the uppermost .6 in. layer to be the first crack life of the overlay.

Table B1 First Crack Effective Repetitions for 1.2" Overlay

LAYER	Mr (psi)	THICKNESS (in)
OVERLAY	400000, 1000000, 70000	1.2
OLD AC	70000, 40000, 20000	4
CRUSHED STONE BASE	16000	8
SOIL SUBGRADE	16000, 8000, 4000	

Overlay Legend

Layer 2	Th = .6"
Layer 1	Th = .6"

OLD AC Mr 70000 SOIL Mr 4000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	22000000	
1000000	1	361000	
	1		1400000

OLD AC Mr 40000 SOIL Mr 4000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	161000	
1000000	1	30500	
	1		88000

OLD AC Mr 20000 SOIL Mr 4000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	4600	
1000000	1	3700	
	1		5700

OLD AC Mr 70000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	7820000	
1000000	1	336000	
	1		1200000

OLD AC Mr 40000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	113000	
1000000	1	29900	
	1		78000

OLD AC Mr 20000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	4000	
1000000	1	4000	
	1		5200

OLD AC Mr 70000 SOIL Mr 16000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	3950000	
1000000	1	291000	
	1		1000000

OLD AC Mr 40000 SOIL Mr 16000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	96500	
1000000	1	29200	
	1		73000

OLD AC Mr 20000 SOIL Mr 16000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	3600	
1000000	1	4000	
	1		5000

NOTE: Layer 2 is not used in calculations because of non-convergence in Chevron 5L computer program.

Table B2 Comparison of Two Pavement Thicknesses With 1.2" Overlay

PAVEMENT 1

LAYER	Mr (psi)	THICKNESS (in)
OVERLAY	400000, 1000000, 70000	1.2
OLD AC	40000	4.0
CRUSHED STONE BASE	16000	8.0
SOIL SUBGRADE	16000, 8000, 4000	

PAVEMENT 2

LAYER	Mr (psi)	THICKNESS (in)
OVERLAY	400000, 1000000, 70000	1.2
OLD AC	40000	6.0
CRUSHED STONE BASE	16000	18.0
SOIL SUBGRADE	16000, 8000, 4000	

PAVEMENT 1

OLD AC Mr 40000 SOIL Mr 4000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	161000	
1000000	1	30500	
	1		88000

OLD AC Mr 40000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	113000	
1000000	1	29900	
	1		78000

OLD AC Mr 40000 SOIL Mr 16000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	95600	
1000000	1	29200	
	1		73000

PAVEMENT 2

OLD AC Mr 40000 SOIL Mr 4000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	218000	
1000000	1	51000	
	1		139000

OLD AC Mr 40000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	161000	
1000000	1	46000	
	1		117000

OLD AC Mr 40000 SOIL Mr 16000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	130000	
1000000	1	42000	
	1		102000

NOTE: Layer 2 is not used in calculations because of non-convergence in the Chevron 5L program.

Table B3 First Crack Repetitions for 2.4" Overlay

Layer	Mr (psi)	Thickness (in)
Overlay	400000, 1000000, 70000	2.4
Old AC	70000, 40000, 20000	4
Crushed Stone Base	16000	8
Soil Subgrade	16000, 8000, 4000	

Overlay Legend

Layer 4 Th = .6"
Layer 3 Th = .6"
Layer 2 Th = .6"
Layer 1 Th = .6"

OLD AC Mr 40000 SOIL Mr 4000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	55800	
1000000	1	81200	
	1		83000
400000	2	118000	
1000000	2	67100	
	2		209000
400000	3	2450000	
1000000	3	141000	
	3		714000

OLD AC Mr 40000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	59300	
1000000	1	102000	
	1		92000
400000	2	103000	
1000000	2	74800	
	2		214000
400000	3	1360000	
1000000	3	129000	
	3		647000

OLD AC Mr 40000 SOIL Mr 16000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	61700	
1000000	1	133000	
	1		100000
400000	2	94400	
1000000	2	81200	
	2		219000
400000	3	855000	
1000000	3	114000	
	3		580000

OLD AC Mr 70000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	379000	
1000000	1	313000	
	1		472000
400000	2	773000	
1000000	2	262000	
	2		1100000
400000	3	22000000	
1000000	3	623000	
	3		3500000

OLD AC Mr 20000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	12600	
1000000	1	42500	
	1		22000
400000	2	16400	
1000000	2	23400	
	2		46000
400000	3	118000	
1000000	3	26700	
	3		120000

Note: Layer 4 is not included in calculations because of non-convergence in the Chevron 5L computer program.

Table B4 Comparison of Two Pavement Thicknesses With 2.4" Overlay

PAVEMENT 1

Layer	Mr (psi)	Thickness (in)
Overlay	400000, 1000000, 70000	2.4
Old AC	40000	4.0
Crushed Stone Base	16000	8.0
Soil Subgrade	16000, 8000, 4000	

PAVEMENT 2

Layer	Mr (psi)	Thickness (in)
Overlay	400000, 1000000, 70000	2.4
Old AC	40000	6.0
Crushed Stone Base	16000	18.0
Soil Subgrade	16000, 8000, 4000	

PAVEMENT 1

OLD AC Mr 40000 SOIL Mr 4000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	55800	
1000000	1	81200	
	1		83000
400000	2	118000	
1000000	2	67100	
	2		209000
400000	3	2450000	
1000000	3	141000	
	3		714000

OLD AC Mr 40000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	59300	
1000000	1	102000	
	1		92000
400000	2	103000	
1000000	2	74800	
	2		214000
400000	3	1360000	
1000000	3	129000	
	3		647000

OLD AC Mr 40000 SOIL Mr 16000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	61700	
1000000	1	133000	
	1		100000
400000	2	94400	
1000000	2	81200	
	2		219000
400000	3	855000	
1000000	3	114000	
	3		580000

PAVEMENT 2

OLD AC Mr 40000 SOIL Mr 4000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	96500	
1000000	1	170000	
	1		150000
400000	2	161000	
1000000	2	114000	
	2		339000
400000	3	2250000	
1000000	3	194000	
	3		1000000

OLD AC Mr 40000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	88400	
1000000	1	170000	
	1		140000
400000	2	140000	
1000000	2	111000	
	2		311000
400000	3	1460000	
1000000	3	160000	
	3		837000

OLD AC Mr 40000 SOIL Mr 16000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	82800	
1000000	1	176000	
	1		134000
400000	2	121000	
1000000	2	105000	
	2		288000
400000	3	1050000	
1000000	3	146000	
	3		744597

Note: Layer 4 is not included in calculations because of non-convergence in the Chevron 5L computer program.

Table B5 First Crack Repetitions for 3.6" Overlay

Layer	Mr (psi)	Thickness (in)
Overlay	400000, 1000000, 70000	3.6
Old AC	70000, 40000, 20000	4
Crushed Stone Base	16000	8
Soil Subgrade	16000, 8000, 4000	

Overlay Legend

Layer 6 Th = .6"
Layer 5 Th = .6"
Layer 4 Th = .6"
Layer 3 Th = .6"
Layer 2 Th = .6"
Layer 1 Th = .6"

OLD AC Mr 40000 SOIL Mr 4000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	143000	
1000000	1	313000	
	1		233000
400000	2	161000	
1000000	2	236000	
	2		454000
400000	3	213000	
1000000	3	187000	
	3		725000
400000	4	495000	
1000000	4	165000	
	4		1120000
400000	5	20600000	
1000000	5	436000	
	5		2790000

OLD AC Mr 40000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	183000	
1000000	1	471000	
	1		306000
400000	2	183000	
1000000	2	313000	
	2		565000
400000	3	213000	
1000000	3	229000	
	3		856000
400000	4	401000	
1000000	4	170000	
	4		1220000
400000	5	7800000	
1000000	5	348000	
	5		2500000

OLD AC Mr 40000 SOIL Mr 16000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	224000	
1000000	1	676000	
	1		384000
400000	2	202000	
1000000	2	420000	
	2		684000
400000	3	208000	
1000000	3	262000	
	3		982000
400000	4	338000	
1000000	4	181000	
	4		1330000
400000	5	4330000	
1000000	5	313000	
	5		2420000

OLD AC Mr 70000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	656000	
1000000	1	997000	
	1		987000
400000	2	596000	
1000000	2	705000	
	2		1780000
400000	3	656000	
1000000	3	471000	
	3		2550000
400000	4	1220000	
1000000	4	389000	
	4		3500000
400000	5	43400000	
1000000	5	913000	
	5		7000000

OLD AC Mr 20000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	63000	
1000000	1	253000	
	1		112000
400000	2	60000	
1000000	2	160000	
	2		204000
400000	3	68000	
1000000	3	102000	
	3		306000
400000	4	127000	
1000000	4	77000	
	4		445000
400000	5	1900000	
1000000	5	137000	
	5		924000

Note: Layer 6 is not included in calculations because of non-convergence in the Chevron 5L computer program.

Table B6 Comparison of Two Pavement Thicknesses With 3.6" Overlay

PAVEMENT 1

Layer	Mr (psi)	Thickness (in)
Overlay	400000, 1000000, 70000	3.6
Old AC	40000	4.0
Crushed Stone Base	16000	8.0
Soil Subgrade	16000, 8000, 4000	

PAVEMENT 2

Layer	Mr (psi)	Thickness (in)
Overlay	400000, 1000000, 70000	3.6
Old AC	40000	6.0
Crushed Stone Base	16000	18.0
Soil Subgrade	16000, 8000, 4000	

PAVEMENT 1

OLD AC Mr 40000 SOIL Mr 4000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	143000	
1000000	1	313000	
	1		233000
400000	2	161000	
1000000	2	236000	
	2		454000
400000	3	213000	
1000000	3	187000	
	3		725000
400000	4	495000	
1000000	4	165000	
	4		1120000
400000	5	20600000	
1000000	5	436000	
	5		2790000

OLD AC Mr 40000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	183000	
1000000	1	471000	
	1		306000
400000	2	183000	
1000000	2	313000	
	2		565000
400000	3	213000	
1000000	3	229000	
	3		856000
400000	4	401000	
1000000	4	170000	
	4		1220000
400000	5	7800000	
1000000	5	348000	
	5		2500000

OLD AC Mr 40000 SOIL Mr 16000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	224000	
1000000	1	676000	
	1		384000
400000	2	202000	
1000000	2	420000	
	2		684000
400000	3	208000	
1000000	3	262000	
	3		982000
400000	4	338000	
1000000	4	181000	
	4		1330000
400000	5	4330000	
1000000	5	313000	
	5		2420000

PAVEMENT 2

OLD AC Mr 40000 SOIL Mr 4000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	302000	
1000000	1	735000	
	1		501000
400000	2	294000	
1000000	2	509000	
	2		920000
400000	3	319000	
1000000	3	336000	
	3		1350000
400000	4	578000	
1000000	4	245000	
	4		1880000
400000	5	12000000	
1000000	5	490000	
	5		3690000

OLD AC Mr 40000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	302000	
1000000	1	801000	
	1		508000
400000	2	278000	
1000000	2	509000	
	2		906000
400000	3	278000	
1000000	3	336000	
	3		1300000
400000	4	466000	
1000000	4	229000	
	4		1760000
400000	5	7420000	
1000000	5	404000	
	5		3220000

OLD AC Mr 40000 SOIL Mr 16000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	294000	
1000000	1	873000	
	1		503000
400000	2	263000	
1000000	2	551000	
	2		888000
400000	3	256000	
1000000	3	324000	
	3		1260000
400000	4	401000	
1000000	4	221000	
	4		1680000
400000	5	4760000	
1000000	5	361000	
	5		2930000

Note: Layer 6 is not included in calculations because of non-convergence in the Chevron 5L computer program.

Table B7 First Crack Repetitions for 4.8" Overlay

Layer	Mr (psi)	Thickness (in)
Overlay	400000, 1000000, 70000	4.8
Old AC	70000, 40000, 20000	4
Crushed Stone Base	16000	8
Soil Subgrade	16000, 8000, 4000	

Overlay Legend

Layer 8 Th = .6"
Layer 7 Th = .6"
Layer 6 Th = .6"
Layer 5 Th = .6"
Layer 4 Th = .6"
Layer 3 Th = .6"
Layer 2 Th = .6"
Layer 1 Th = .6"

OLD AC Mr 40000 SOIL Mr 4000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	390000	
1000000	1	1040000	
	1		657000
400000	2	379000	
1000000	2	767000	
	2		1160000
400000	3	390000	
1000000	3	574000	
	3		1680000
400000	4	401000	
1000000	4	436000	
	4		2190000
400000	5	495000	
1000000	5	336000	
	5		2760000
400000	6	1130000	
1000000	6	302000	
	6		3540000
400000	7	58600000	
1000000	7	836000	
	7		6790000

OLD AC Mr 40000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	565000	
1000000	1	1680000	
	1		960000
400000	2	495000	
1000000	2	1140000	
	2		1630000
400000	3	452000	
1000000	3	801000	
	3		2250000
400000	4	426000	
1000000	4	551000	
	4		2820000
400000	5	452000	
1000000	5	375000	
	5		3460000
400000	6	855000	
1000000	6	302000	
	6		4170000
400000	7	20700000	
1000000	7	649000	
	7		6610000

OLD AC Mr 40000 SOIL Mr 16000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	748000	
1000000	1	2530000	
	1		1300000
400000	2	616000	
1000000	2	1680000	
	2		2160000
400000	3	526000	
1000000	3	1070000	
	3		2890000
400000	4	439000	
1000000	4	705000	
	4		3500000
400000	5	426000	
1000000	5	420000	
	5		4150000
400000	6	678000	
1000000	6	302000	
	6		4790000
400000	7	9670000	
1000000	7	530000	
	7		6700000

Note: Layer 8 is not included in calculations because of non-convergence in the Chevron 5L computer program.

-Table B7 continued on next page-

-Table B7 continued-

OLD AC Mr 70000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	1580000	
1000000	1	2980000	
	1		2500000
400000	2	1260000	
1000000	2	2050000	
	2		4090000
400000	3	1020000	
1000000	3	1450000	
	3		5420000
400000	4	885000	
1000000	4	997000	
	4		6550000
400000	5	885000	
1000000	5	649000	
	5		7600000
400000	6	1580000	
1000000	6	490000	
	6		8810000
400000	7	43400000	
1000000	7	1140000	
	7		13100000

OLD AC Mr 20000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	230000	
1000000	1	997000	
	1		412000
400000	2	208000	
1000000	2	649000	
	2		710000
400000	3	197000	
1000000	3	436000	
	3		990000
400000	4	192000	
1000000	4	302000	
	4		1260000
400000	5	219000	
1000000	5	214000	
	5		1550000
400000	6	439000	
1000000	6	170000	
	6		1930000
400000	7	9670000	
1000000	7	361000	
	7		3270000

Note: Layer 8 is not included in calculations because of non-convergence in the Chevron 5L computer program.

Table B8 Comparison of Two Pavement Thicknesses With 4.8" Overlay

PAVEMENT 1

Layer	Mr (psi)	Thickness (in)
Overlay	400000, 1000000, 70000	4.8
Old AC	40000	4.0
Crushed Stone Base	16000	8.0
Soil Subgrade	16000, 8000, 4000	

PAVEMENT 2

Layer	Mr (psi)	Thickness (in)
Overlay	400000, 1000000, 70000	4.8
Old AC	40000	6.0
Crushed Stone Base	16000	18.0
Soil Subgrade	16000, 8000, 4000	

PAVEMENT 1

OLD AC Mr 40000 SOIL Mr 4000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	390000	
1000000	1	1040000	
	1		657000
400000	2	379000	
1000000	2	767000	
	2		1160000
400000	3	390000	
1000000	3	574000	
	3		1680000
400000	4	401000	
1000000	4	436000	
	4		2190000
400000	5	495000	
1000000	5	336000	
	5		2760000
400000	6	1130000	
1000000	6	302000	
	6		3540000
400000	7	58600000	
1000000	7	836000	
	7		6790000

OLD AC Mr 40000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	565000	
1000000	1	1680000	
	1		960000
400000	2	495000	
1000000	2	1140000	
	2		1630000
400000	3	452000	
1000000	3	801000	
	3		2250000
400000	4	426000	
1000000	4	551000	
	4		2820000
400000	5	452000	
1000000	5	375000	
	5		3460000
400000	6	855000	
1000000	6	302000	
	6		4170000
400000	7	20700000	
1000000	7	649000	
	7		6610000

OLD AC Mr 40000 SOIL Mr 16000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	748000	
1000000	1	2530000	
	1		1300000
400000	2	616000	
1000000	2	1680000	
	2		2160000
400000	3	526000	
1000000	3	1070000	
	3		2890000
400000	4	439000	
1000000	4	705000	
	4		3500000
400000	5	426000	
1000000	5	420000	
	5		4150000
400000	6	678000	
1000000	6	302000	
	6		4790000
400000	7	9670000	
1000000	7	530000	
	7		6700000

Note: Layer 8 is not included in calculations because of non-convergence in the Chevron 5L computer program.

-Table B8 continued on next page-

-Table B8 continued-

PAVEMENT 2

OLD AC Mr 40000 SOIL Mr 4000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	885000	
1000000	1	2400000	
	1		1490000
400000	2	800000	
1000000	2	1680000	
	2		2580000
400000	3	700000	
1000000	3	1200000	
	3		3530000
400000	4	510000	
1000000	4	801000	
	4		4160000
400000	5	636000	
1000000	5	530000	
	5		4960000
400000	6	1170000	
1000000	6	404000	
	6		5910000
400000	7	28600000	
1000000	7	836000	
	7		9070000

OLD AC Mr 40000 SOIL Mr 8000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	948000	
1000000	1	2820000	
	1		1620000
400000	2	800000	
1000000	2	1850000	
	2		2710000
400000	3	678000	
1000000	3	1320000	
	3		3660000
400000	4	578000	
1000000	4	836000	
	4		4450000
400000	5	543000	
1000000	5	530000	
	5		5160000
400000	6	916000	
1000000	6	361000	
	6		5970000
400000	7	15200000	
1000000	7	705000	
	7		8550000

OLD AC Mr 40000 SOIL Mr 16000

OVERLAY Mr	LAYER	BASIC REPS	EFFECTIVE REPS
400000	1	982000	
1000000	1	3340000	
	1		1710000
400000	2	827000	
1000000	2	2050000	
	2		2840000
400000	3	678000	
1000000	3	1380000	
	3		3780000
400000	4	543000	
1000000	4	873000	
	4		4540000
400000	5	480000	
1000000	5	530000	
	5		5200000
400000	6	748000	
1000000	6	348000	
	6		5920000
400000	7	9670000	
1000000	7	598000	
	7		8050000

Note: Layer 8 is not included in calculations because of non-convergence in the Chevron 5L computer program.

APPENDIX C

RESULTS OF LABORATORY TESTS ON ASPHALT CONCRETE OVERLAY CORES FROM ITD PAVEMENTS

In order to determine if different asphalt concrete mixtures affect overlay performance life, we requested that ITD look at overlay fatigue cracking performance life in the state and obtain, for our testing, cores from selected overlays that reflected above, average and below average performance life.

Listed in Table C-1 are the selected overlay pavements and the mechanical properties of the overlay cores. A large range of modulus and indirect tensile strength results from the tests.

Strain toughness was calculated from the modulus and indirect tensile strength for each set of cores and is listed in approximate descending order in Table C-2. High toughness means more resistance to fatigue cracking, leading to a longer performance life.

Also listed in Table C-2 is the ITD fatigue cracking ranking, with descending order of performance life. A reasonable match exists. Although SH-53 and I-15 core tests show a reverse outcome as compared to their corresponding strain toughness values, this overall field-test effort indicates that strain toughness of asphalt mix may be a reasonable indicator of fatigue cracking performance life. Thus, a strain toughness calculation in the laboratory may be significant toward prediction of fatigue cracking performance life for a specific asphalt concrete mix planned for construction. Further field-test investigation is

TABLE C-1 MECHANICAL PROPERTIES OF PAVEMENT CORES

PAVEMENT IDENTIFICATION	AVE. MECHANICAL PROPERTIES	
	Mr (1000 psi)*	ITS (psi)**
I-90 (MP3)	141	92
Chinden Blvd (44th to Coffey) Boise	265	170
SH-53 (MP53)	257	122
I-15 (MP44)	176	96
I-84 (MP145)	335	133
I-84 (MP175)	733	211

*Resilient Modulus is total modulus at .1 sec. loading at 77F.
**Indirect Tensile Strength performed at 2 in. per min. vertical deformation rate at 77F.

TABLE C-2 STRAIN TOUGHNESS VS. QUALITATIVE FIELD PERFORMANCE

PAVEMENT CORE	* MEAN STRAIN TOUGHNESS (10E-7)	PERCENT VARIATION	** FATIGUE CRACKING FIELD PERFORMANCE
I-90 (MP31)	2.16	11	Above Average
Chinden Blvd	2.11	23	Above Average
SH-53 (MP53)	1.13	14	Above Average
I-15 (MP44)	1.58	23	Average
I-84 (MP145)	0.86	55	Below Average
I-84 (MP175)	0.41	12	Below Average

* $\dfrac{(\text{Indirect Tensile Strength})^2}{2\,(\text{Resilient Modulus})^2}$

** General opinion by Idaho Transportation Department on a statewide basis.

needed to establish the reliability of this approach.

If the strain toughness "parameter" proves reliable, a method must exist to include this in the prediction of fatigue cracking life (and overlay design). Consequently, Appendix D, which follows, is a method to do this; the fatigue cracking equation for representation of the specific asphalt concrete mix is adjusted based on the value of the strain toughness.

APPENDIX D

ADJUSTMENT OF BASIC FATIGUE LIFE EQUATION FOR RELATIVE TOUGHNESS OF ASPHALT CONCRETE OVERLAY MIX

The application of the basic fatigue life equation is described in Appendix A. This equation is

$$N = C\varepsilon^{-5.16}$$

where

N = basic fatigue life to first crack (repetitions),

C = Constant, inversely proportional to modulus of asphalt concrete, with values shown in Figure A-1 of Appendix A (repetitions), and

ε = maximum tensile radial or "bending" strain at bottom of overlay layer being investigated under wheel loading, (in this case a set of dual wheels, 4500 lb. per wheel, 80 psi tire pressure, 13 in. C-C to represent effective loading of a 18 kip single axle equivalent).

The constant C is also adjusted upward or downward due to the relative toughness of the asphalt concrete mix. The steps for this adjustment follow:

1. The values of C versus asphalt concrete mixture modulus are obtained from Figure A-1. These values of C correspond to <u>average</u> fatigue cracking performances of asphalt concrete overlay mix, statewide. Note that more than one value of C if obtained from Figure A-1 due to the difference in modulus associated with seasons of the year (see Appendix A procedure).

2. Two laboratory tests are performed on appropriately aged test specimens of the asphalt concrete mix. They are:

   a. Indirect tensile strength at standard temperature, and

   b. Resilient modulus (preferably total modulus) at same standard temperature of the indirect tensile strength.

3. Each of the above values of the indirect tensile strength and resilient (total) modulus at standard temperature are divided by the corresponding state average values to obtain the strength and modulus ratios TSR and MrR, respectively. TSR and MrR can be greater, equal or less than 1.0. (TSR and MrR greater

than 1.0 indicate that the overlay mix has greater test values than the state average overlay mix.)

4. The relative strain toughness RT is calculated using the previous ratios:

$$RT = \frac{(TSR)^2}{(MrR)^2}$$

5. The basic fatigue life equation can be rewritten as:

$$\varepsilon = AN^S$$ where

A is a new constant and S is -(1/5.16). Past fatigue test data indicate that the relative change of A between two different asphalt concrete mixtures is approximately equal to their relative toughness (RT) at N = 1 x 10^5 repetitions of strain fatigue life.

RT is modified to consider statistical reliability of the RT outcome in the field. Thus, RT is brought closer to the state average of RT = 1 by halving the relative toughness difference. This value of RT is denoted by RTS, where:

$$RTS = \frac{RT+1}{2}$$

6. Rearrangement back to the basic fatigue life equation in the form of $N = C\varepsilon^{-5.16}$ shows that the adjusted value of the C constant for relative toughness is:

$$C_{adj} = C(RTS)^{5.16}$$ where

C_{adj} = adjusted value of C due to relative strain toughness

7. The basic fatigue life equation adjusted for asphalt concrete mix relative toughness is therefore:

$$N = C_{adj}\ \varepsilon^{-5.16}$$

<u>Example for Overlay Mix G</u>

Suppose at spring-fall seasonal conditions the asphalt concrete overlay temperature is determined to have a modulus of 400,000 psi. From Figure A-1, the value of C for the state average overlay mix (fatigue cracking life is average) is 1.7 x 10^{-14}.

Also suppose that the following laboratory test data exist for overlay mix G and the "state average mix" at a standard test temperature:

	Indirect Tensile Strength, psi	Resilient (Total) Modulus, psi
State Average Mix	80	300,000
Mix G	90	275,000

Then, TSR = 90/80 = 1.125 and MrR = 275000/300000 = .917. Thus, RT = $(TSR)^2/(MrR)^2 = (1.125)^2/(.917)^2 = 1.5$ for mix G.

$$RTS = \frac{RT+1}{2} = 1.25$$

The adjusted C for mix G is:

$$\begin{aligned} C_{adj} &= C(RTS)^{5.16} \\ &= 1.7 \times 10^{-14} \ (1.25)^{5.16} \\ &= 5.4 \times 10^{-14} \end{aligned}$$

For mix G, the adjusted C of 5.4×10^{-14} is used instead of the state standard C of 1.7×10^{-14} in the basic fatigue life equation for the spring-fall season.

The basic fatigue life equation for mix G in the spring-fall season is:

$$N = 5.4 \times 10^{-14} \ \varepsilon^{-5.16}$$

A similar calculation procedure for C adj. is done for the other seasons using the same RT of 1.5. RT is assumed to be constant for mix G. Then, the associated basic fatigue life equations are determined and are used in the procedure described in Appendix A.